

Multifragmentation through Exotic Shape Nuclei in $\alpha(5\text{GeV/u}) + \text{Au}$ Reactions

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Abstract

We simulate the fragmentation processes in the $\alpha + \text{Au}$ collisions at a bombarding energy of 5 GeV/u using the simplified RQMD approach plus the statistical decay model. We find from the simulation that the angular-distribution of the intermediate mass fragments has a sideward peak, more strongly in the transverse direction than in the beam-direction, when the intermediate nucleus formed by the dynamical process has an annular eclipse shape, which explains the experimental results.

Multifragmentation has been attracting attention as one of the most important aspects of light- and heavy- ion reactions in the intermediate and high energy region [1,2]. It is speculated that the decay of a highly excited nuclear system carries the information about the nuclear equation of state (EOS) and the liquid-gas phase transition of low density nuclear matter.

The very interesting results have been reported by the KEK experimental group for the angular-distribution of the intermediate mass fragments (IMF) in proton (12 GeV) and alpha (5 GeV/u) induced reactions [3]. There are two components in the experimental data for the angular-distribution of IMF: one is forward peaking, and the other has a sideward peak at $\theta_{\text{lab}} = 70^\circ$. Recently this group has made new experiments of the proton induced reactions to choose only the central events using two coincident IMFs with the opposite azimuthal direction on the *Au* target [4]. The component with the forward peak disappear, and the sideward peak is enhanced very much and can be seen clearly even in the logarithmic scale [4].

In this reaction we consider that some high energy pions, protons and light fragments such as deuteron are emitted forwards immediately after starting the collision, followed by IMFs created through the thermal decay of a hot intermediate nucleus. If the hot intermediate nucleus decays isotropically, the angular-distribution of IMF should have a forward peak. Hence the sideward peak should be explained by the hypothesis that the intermediate nucleus has an exotic shape and expands more strongly in the transverse direction than in the beam-direction.

In the past Hüffner and Sommermann [5] suggested the trumpet-shaped hole to explain the enhanced backward emission of heavy fragments in high energy proton-induced reactions. In recent years, moreover, the decay from the non-spherical nuclei has been suggested for the multifragmentation in heavy-ion collisions [6–9].

In this letter we theoretically analyze the fragmentation processes of $\alpha(5\text{GeV/u}) + \text{Au}$ reaction, and discuss the relation between the angular-distribution and the shape of the intermediate nucleus. We choose only the alpha- induced reaction here since at the bombarding

energies of 12 GeV the elementary processes of two-body collisions are too complicated for many open channels. Furthermore our study is restricted only to the central events for the reason mentioned above.

Our purpose is to clarify the fragmentation mechanism qualitatively, particularly in view of the shape of the intermediate nucleus. For this purpose we should use a dynamical model which automatically give the nuclear phase-space distribution at the intermediate time stage, which has to be assumed in statistical calculations [2,5,8]. The Quantum Molecular Dynamics (QMD) approach [10] is commonly used as a dynamical model for the theoretical study of fragmentation. In this approach baryons are described as Gaussian wave packets, and their dynamical motions are given by a mean-field and two-body collisions. Toshiki Maruyama et al. [11] and T. C. Sangster et al. [12] have succeeded to reproduce experimental data of fragment multiplicities in heavy-ion collisions around several 10 MeV/u by using QMD together with the statistical decay model [13,14].

At relativistic energies the Lorentz covariant transport approach is desired because all nuclei and fragments must hold the consistent phase-space distribution under the Lorentz transformation. In fact, these relativistic effects clearly appear in the multiplicity of alpha particles in the heavy-ion collisions even at $E_{\text{lab}} \sim 1$ GeV/u [15]. Therefore the Relativistic QMD (RQMD) approach [16,17] should be the most useful theoretical model for the present purpose.

In order to reduce the computation time, we use the simplified version of RQMD (RQMD/S) [18], where we take the time fixations to equalize all time coordinates of particles in the reference frame. This new definition still hold the Lorentz covariance in the mean-field. In Ref. [18], then, we have confirmed that the RQMD/S give almost the same results as the full RQMD up to 6 GeV/u for the transverse flow, which is thought to be the most sensitive observables to relativistic effects at present [19]. In the treatment of the two-body collisions, furthermore, we use the prescription of Ref. [20] to keep the Lorentz covariance in the collisions within our time-fixation scheme around several GeV/u energy region [20,21].

Now we investigate the origin of the experimental results for the IMF angular-distribution by simulating the dynamical stage of $\alpha(5 \text{ GeV/u}) + \text{Au}$ collisions with RQMD/S. The actual calculations are made in the following way. First the initial distribution at rest is generated by the cooling method [22] and boosted according to the bombarding energy. Second we perform the RQMD/S calculations and obtain the dynamical fragment distribution. Third we boost each dynamical fragment to its rest frame and evaluate its excitation energy. Finally we calculate the statistical decay [13] from the dynamical fragments and obtain the final fragment distribution.

We use a Skyrme-type interaction with 'hard' EOS (the incompressibility $K = 380 \text{ MeV}$) parameterized in Refs. [10,23] for the effective interactions. In addition, the symmetry force and the Coulomb force is introduced to get a correct isospin of a fragment in the simulation. The Lorentz scalar Coulomb force can give correct effects to particle motions in a relatively low energy region inside the fast moving matter.

For the cross-section of two baryon collisions we use the Cugnon's parameterization [24] for an elastic channel and the Wolf's formulation [21,25] for inelastic channels including three baryonic resonances: Δ , $N^*(1440)$ and $N^*(1535)$. These resonances can decay into nucleons and mesons (π and η) [25]. As for the parameters of the inelastic channels we use the values used in Ref. [26], since the parameters in Ref. [21,25] give unphysical large cross sections above $E_{\text{lab}} = 1.5 \text{ GeV}$ [26].

In the fragmentation process the mean-field at low density is considered to play an important role [6]. In order to simulate the low density behavior we use two kinds of the width parameter L for the Gaussian wave packets. The first (case I) is defined by $L = 0.92 \text{ fm}$ given by Ref [11], and the second (case II) by $L = 0.625 \text{ fm}$. The Gaussian width does not affect bulk properties of ground states made by the cooling method [22]. In the dynamical process, however, the difference of these two cases should describe the different instability in the low density region: in the dilute medium the attractive force between nucleons are stronger in the case I than in the case II.

We show the baryon and pion distributions in the coordinate space with a 12 fm/c time

step, projecting on the xz - plane, restricted with positions $|y| < 1$ fm (upper columns), and the xy - plane, restricted with positions $|z| < 1$ fm (lower column), in Fig. 1 (case I) and in Fig. 2 (case II). There z -axis and xy -plane are defined as the beam-direction and the reaction plane, respectively. These figures include results of twenty simulations for an impact-parameter $b = 0$ fm, and the blue, red, and yellow circles denote the nucleons, baryonic resonances and mesons, respectively.

Around the time step $t = 16$ fm/c a lot of resonances and pions are produced and propagate forwards in both cases. After $t = 28$ fm/c, these high energy pions and nucleons are emitted forwards. At this step, the shapes of the intermediate nuclei are different between the two cases. In Fig. 2 (case II), the empty region appears in the center; namely the intermediate nucleus with the annular eclipse shape is constructed through the reaction. After that this exotic intermediate nucleus slowly expands sideways, and disintegrates into some fragments. Apparently this fragmentation process is the multifragmentation. On the other hand, in Fig. 1 (case I), the whole nucleons expand almost isotropically emitting the nucleons and finally the central part is shrunken again and form one big fragment with the small forwards velocity. Please note that the shape of the intermediate nucleus in the case II is similar to that in Ref. [7]. However both formation processes are quite different, and our process does not produce so clear ring/doughnut shape.

Next we evaluate the angular-distribution of fragments in these two cases. Events are restricted to the impact-parameter $b < 3$ fm because the main contribution to the sideward peak component is to come from central collisions. In the actual calculation we perform six hundred QMD simulations and one hundred cascade calculations of the statistical decay model [13] for each QMD simulation. The numerical errors are found to be negligibly small.

In Fig. 3, we show the angular-distribution of two kinds of fragments with charge $Z = 1$ (open circles) and $3 \leq Z \leq 20$ (IMF) (full squares), for case I in Fig. 3a and for case II in Fig. 3b. In this figure we do not show a comparison with experimental data [3] because the experimental group has given only data for fragments with $Z = 9$, and we do not have enough computer power to get sufficient statistics for individual fragments.

In case I, both the angular-distributions of the two kinds of fragments have a forward peak. In case II, however, the IMF angular-distribution has a sideward peak and this result agrees with the experiment qualitatively. In addition we can see that more IMFs are generated in case II than in case I. We have found in the simulations that this sideward peak of the IMF angular-distribution is very much correlated with the shape of the intermediate nucleus, i.e. the annular eclipse shape.

The difference of the two processes (case I and II) must be caused by properties in the low density region. Immediately after the incident alpha drills a hole in the *Au* target, the baryon-baryon collision process produces the side-directed force to the medium, and the surface along this hole must be very steep. The large Gaussian width in case I, however, makes a gentle surface, and diffuse the density into the hole region. The nucleons along the hole, feeling a rather strong attractive mean-field, are gathered, and form a large compound nucleus. The IMFs are created through the evaporation and the binary fission.

In case II, on the other hand, the small width weakens the attractive mean-field in the low density region, and the transverse expansion becomes stronger than this attractive force. This expansion dilutes the medium, and increases the instability. Then the medium must be vaporized, and multifragmentation occurs. From this consideration we can understand the reason of the larger cross-section in case II (see Fig. 3) as well as the sideward peak.

Finally we would like to comment on the contribution from non-central events. With increase of the impact parameter the peak angle moves forwards. In the middle impact-parameter region the intermediate nucleus has a partial eclipse and expands sideways. Such a process is also responsible for the side-directed peak of the IMF angular-distribution while the peak angle depends on the impact-parameter. However we cannot suppose that two IMFs generated through the partial eclipse shape are observed in the azimuthally opposite directions the IMF-coincidence experiments [4].

On the other hand we can consider the situation that the intermediate nucleus does not have a exotic shape, but has a very large angular-momentum. In this case the intermediate nucleus does not decay isotropically, and two IMFs move to the azimuthally opposite

directions. However the rotational axis must direct almost perpendicularly to the reaction plane, and then the rotation affects the distribution of the azimuthal angle, but not that of the polar angle. Thus the rotation of the intermediate nucleus cannot explain the sideward peak in the first inclusive experiments [3].

To summarize, we have performed the QMD simulation for the $\alpha + \text{Au}$ collision at 5 GeV/u. The dynamical instability in the dilute nuclear medium is simulated by changing the value of the Gaussian width parameters. Then we conclude that this reaction constructs a hot nuclear system with the annular eclipse shape in the central collision. This exotic intermediate nucleus expands sideways and causes multifragmentation. As a result of this process the IMF angular-distribution has a side-directed peak. This confirms findings in experimental results [3,4] showing clear evidence of multifragmentation.

The author would like to thank Prof. H. Horiuchi, Drs. A. Iwamoto, K. Niita, K.H. Tanaka, T. Murakami, Toshiki Maruyama and Mr. H. Ochiishi for the useful discussions. Dr. A. Ohnishi and Mr. Y. Nara give the initial distribution for the RQMD/S simulations. This work is financially supported in part by the RCNP, Osaka University, as a RCNP Computational Nuclear Physics Project (Project No 94-B-04).

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Figure Caption

Fig.1 The time evolution of the baryon and meson distributions in the coordinate space at time steps 4, 16, 28 and 40 fm/c in $\alpha(5 \text{ GeV/u}) + \text{Au}$ collisions for the impact-parameter $b = 0 \text{ fm}$ in case I. The upper columns show the distributions on xz - plane, restricted as $|y| < 1 \text{ fm}$, while the lower columns on xy - plane, restricted as $|z| < 1 \text{ fm}$. The blue, red, and yellow circles denote the nucleons, resonances and mesons, respectively.

Fig.2 The same figure as in the Fig. 1, but for case II.

Fig.3 The angular-distributions of fragments for case I (a) and case II (b): $Z = 1$ (open circles) and $3 \leq Z \leq 20$ (full squares). The cross-section for the second fragment is multiplied by 10. Events are restricted with the impact-parameter $b < 3 \text{ fm}$.

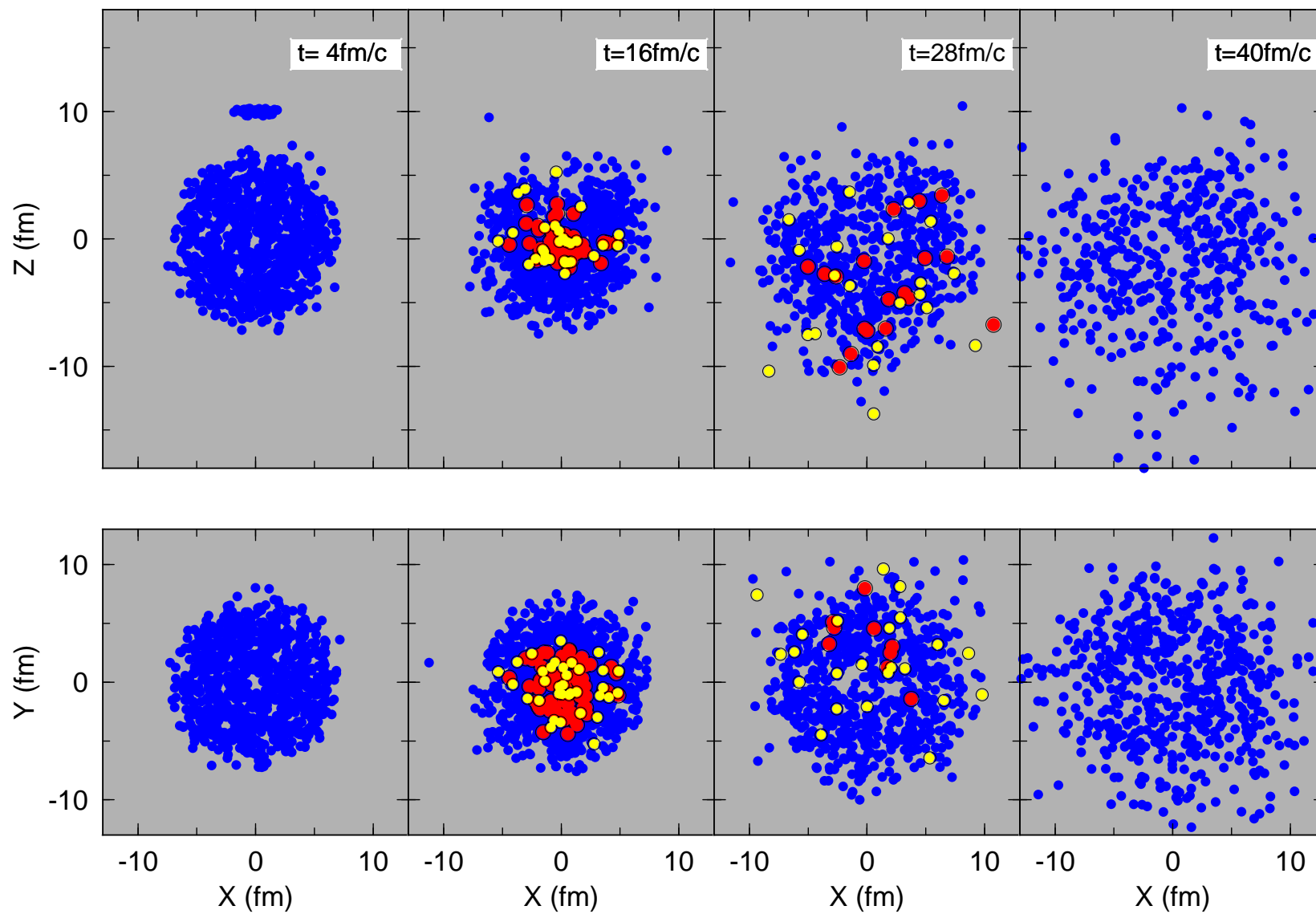


Fig. 1

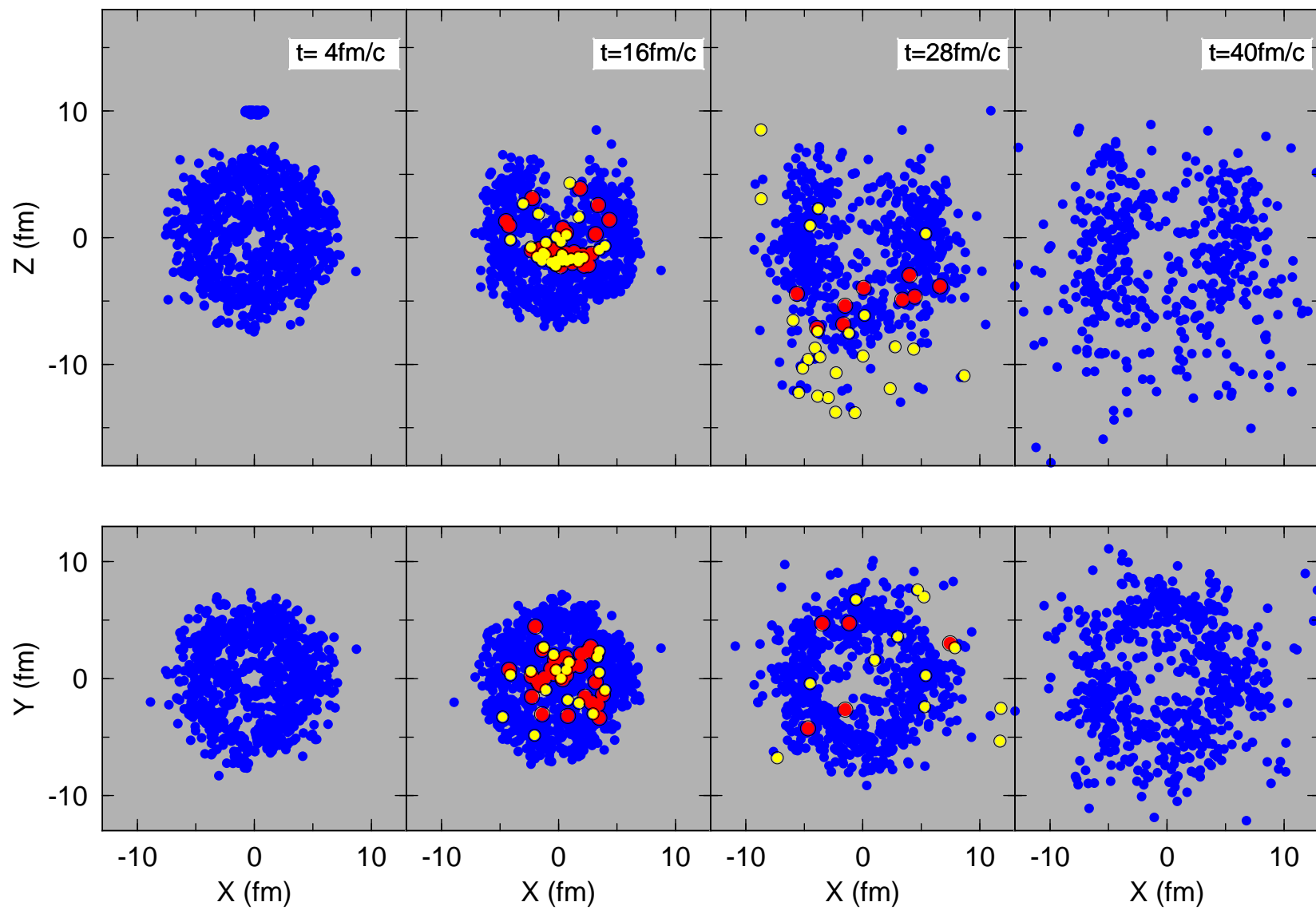


Fig. 2

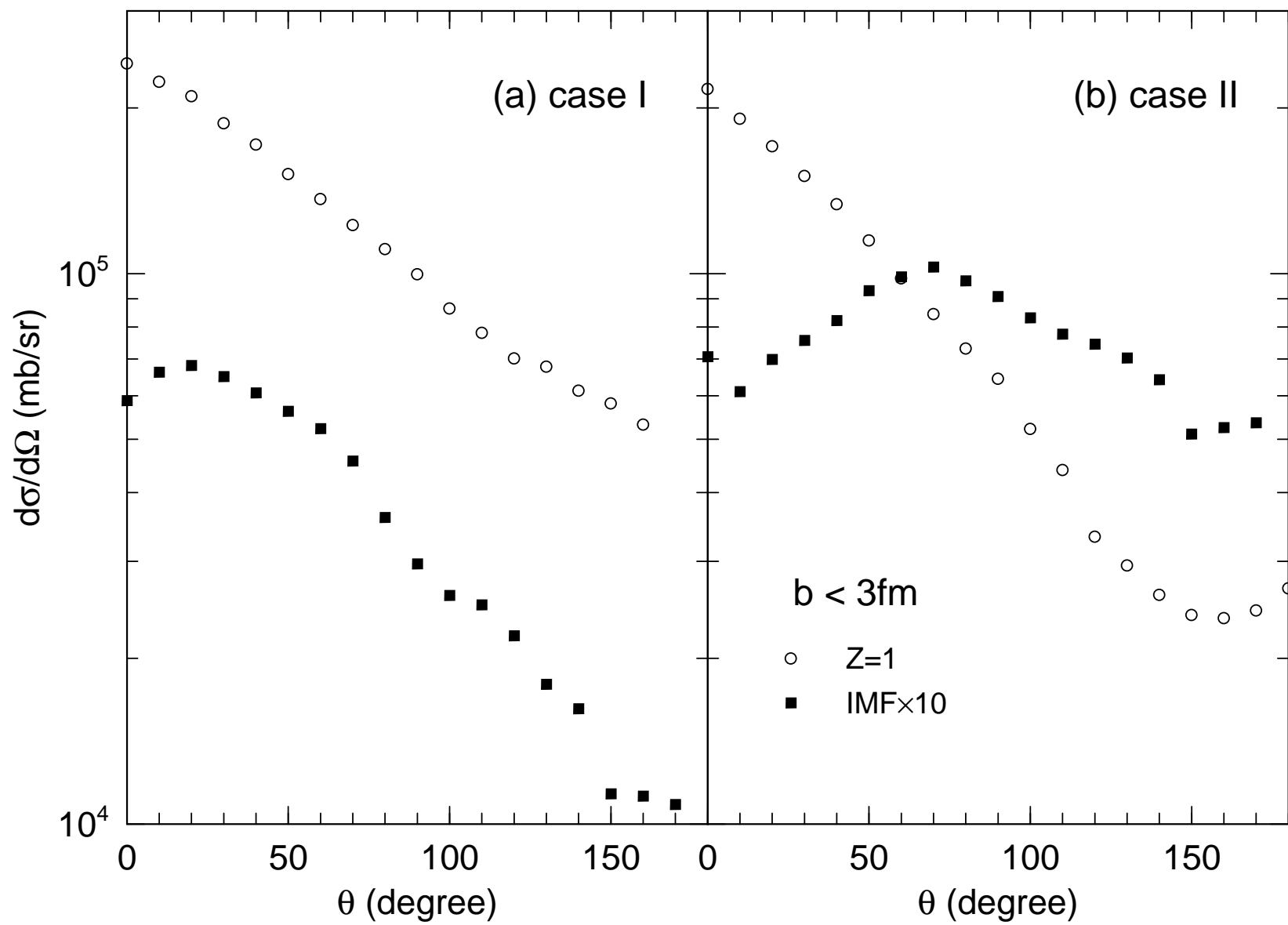


Fig .3